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Beam Dynamics Investigation for the Compact Seeded THz-FEL Amplifier

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Abstract

A compact seeded terahertz (THz) free-electron laser (FEL) amplifier is under development at the Institute of Advanced Energy, Kyoto University. The system consists of a 1.6-cell S-band BNL-type photocathode radio frequency (RF) gun, a focusing solenoid magnet, a magnetic bunch compressor, focusing quadrupoles, a short planar undulator and a THz parametric generator for seeding. The accelerator system will generate a high brightness ultra-short electron bunch injected to the short undulator. Since characteristics of the emitted radiation strongly depend on the electron beam properties, the beam dynamics of the system has been investigated. As the result, the system should be operated at the high accelerating voltage of 80 MV/m to avoid the space-charge effect which causes serious bunch lengthening. The laser with the uniform temporal distribution and the injection phase of 12 degree is suitable for the bunch compression in the chicane. This condition provides the electron beam injected to the undulator with the peak current of more than 300 A and the FWHM bunch length of 0.36 ps at the bunch charge of 200 pC.

Peer-review under responsibility of the organizing committee of the 12th EMSES 2015

Keywords: Beam dynamics, Free-electron lasers, Terahertz, Photocathode

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1. Introduction

Recently, developments of terahertz (THz) science and technology are growing rapidly and widely in many fields. However, a lack of a powerful and compact THz radiation source is still a main issue in the THz science. The free-electron laser (FEL) is one of the good candidates for a compact, a high power and a tunable THz radiation source. The existing compact THz-FEL system is the table-top THz-FEL at KAREI which and has been delivering the peak power up to a few kilowatts [1]. Recent progress of a photocathode RF gun, which can generate a high peak power electron beam by using a small accelerator component [2], realizes a seeded SASE FEL system for X-ray FEL [3]. The idea to use this technology to THz generation has been proposed at Neptune Lab. in UCLA [4] and THz-FEL amplifier at National Tsinghua University, Taiwan [5]. We have also proposed a high brightness, narrow-band, and tunable THz radiation source based on a seeded SASE FEL amplifier at Institute of Advanced Energy, Kyoto University [6], to extend available wavelength region in Kyoto University Free-Electron Lasers (KU-FEL) [7]. The system will consists of a 1.6-cell S-band BNL-type photocathode RF-gun with a photocathode drive laser system, a focusing solenoid magnet, a 4-dipole magnetic chicane bunch compressor, triplet quadrupole magnets, a planar undulator and a THz parametric generator for seeding laser. Since our target is a simple and a compact THz source, the total length will be less than 5 m. For the first stage of the construction, we will generate a coherent synchrotron radiation (CSR) from a short planar undulator with the target wavelength from 300 to 800 μm without the seed laser. For this purpose, a short bunch electron beam generation is required. It is therefore, in this paper, we will report the design of the system configuration and investigations of the beam dynamics to generate short bunch high peak current electron beam. The numerical simulation codes, PARMELA [8] and GPT [9], are used for the multi-particle beam dynamics investigation with 100,000 macro-particles. The schematic view of the developing system without the seeding system is shown in Fig. 1.

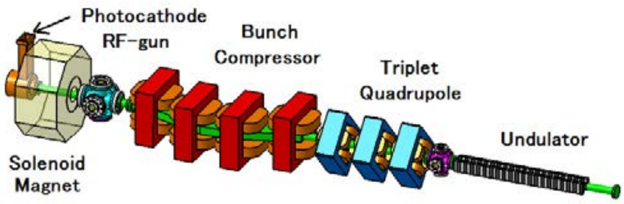

Fig. 1. Schematic view of the Compact Seeded THz-FEL Amplifier.

2. Electron Bunch Generation

The 1.6-cell S-band BNL-type photocathode RF-gun is used as an electron source for the compact THz system. The RF-gun was manufactured by KEK where the performance has been improved since 2008 [10]. The photocathode is illuminated by a UV laser with the wavelength of 266 nm which is generated by a pico-seconds mode-locked Nd:YVO_4 laser [11]. For the beam dynamics investigations of the electron beam from the RF-gun, PARMELA calculation has been performed at a high average accelerating voltage with a low bunch charge. The lasers are injected at a low accelerating RF phase in order to obtain an electron bunch with positive energy chirp, which electrons at the bunch head has lower energy than the bunch tail, suitable for the bunch compression by the magnetic chicane.

Since a low energy electron bunch can easily be deformed by a longitudinal space-charge force, the laser pulses with uniform temporal distribution are employed for generating the temporally uniform electron bunch suitable for a bunch compression. This laser pulse can be produced by using a “Chirped-Pulse Stacking” [12] which consists of three birefringence α-BBO crystal rods. The parameters for the beam dynamic investigation are listed in the Table.1. The simulation results of the beam parameters at the RF-gun exit are shown in Fig. 2.

Table 1. The parameters for the beam dynamic investigation.

Parameters	Values
RF-gun	
Average accelerating field	60, 70, 80 MV/m
Bunch charge	100 to 400 pC
Lasers	
Temporal distribution	Uniform
Pulse length	16 deg
Spatial distribution	Gaussian
Radial size	rms 1 mm cut-off 3 mm.
Injection phase	12, 16, 20 deg

According to the simulation result, the extracting beam from the RF-gun with the accelerating voltage of 60, 70 and 80 MV/m has the average energy of 5.3, 6.2 and 7 MeV, respectively. As shown in Fig. 2 (a), the rms relative energy spread increases at the higher accelerating voltage. The rms bunch length increases slightly when the bunch charge increases (Fig. 2 (b)). The beams size and emittance decrease at the higher accelerating voltage (Fig. 2 (c)) due to less influence from the space-charge effect. The peak current increases proportional to the bunch charge and reaches up to 85 A at accelerating phase of 12 degree and the bunch charge of 400 pC as shown in Fig. 2 (d). In this study, we define the peak current as the maximum current of the current profile with 0.1 ps binning.

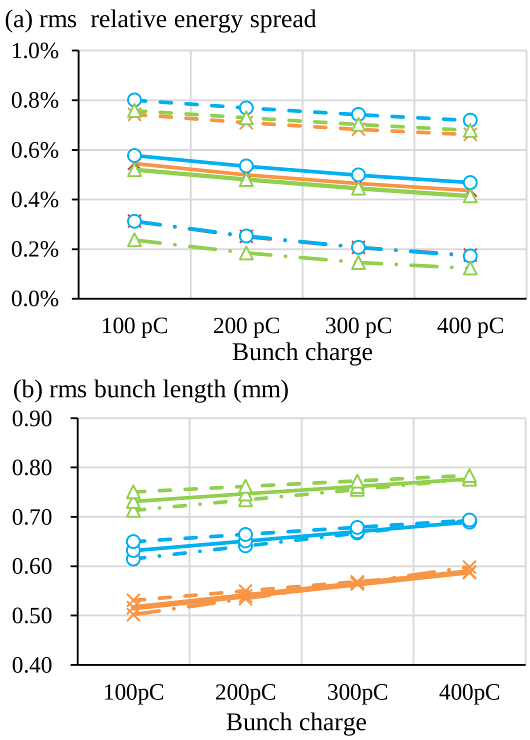

Fig. 2. (a) rms energy spread and (b) rms bunch length

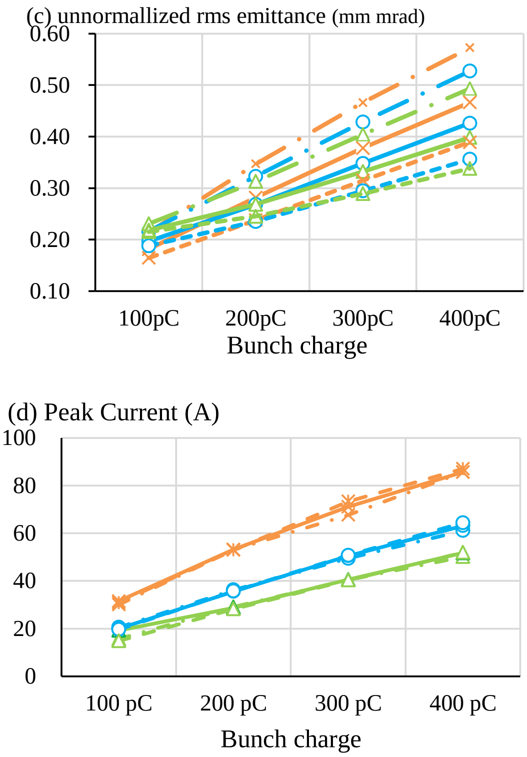

Fig. 2. (Cont.) (c) unnormalized rms emittance and (d) peak current at the RF-gun exit as a function of the bunch charges. (Accelerating voltage - single dot dash line; 60 MV/m, solid line; 70 MV/m, dash line; 80 MV/m, Accelerating phase - cross marker; 12 deg., circle marker; 16 deg., triangle marker; 20 deg.)

To determine the suitable bunch compression condition by the chicane, the energy chirp (h) which is defined by the slope of energy spread (δ) over electron position (t), $h = d\delta/cdt_{t=0}$, has been investigated. The energy chirp was calculated from 90 percent of ahead electrons within the bunch, which is the regime of the linear correlation in longitudinal phase space. The calculation results of the energy chirps shown in Fig. 3. As shown in Fig. 3, it is obvious that the electron beam accelerated by the lower electric field has a smaller energy chirp. The larger acceleration phase beam also has smaller energy chirp. In principle, the smaller energy chirp requires a larger deflection angle for the maximum compression. We will study about the bunch compression in the next section.

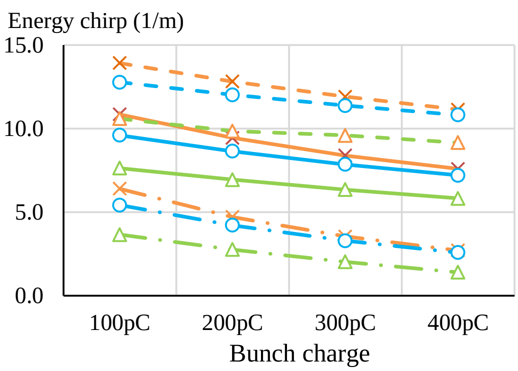

Fig. 3. Energy chirp at the RF-gun exit as a function of the bunch charges. (The description of the lines and the markers is same as Fig. 2)

3. Bunch compression

The 4-rectangular H-type dipole electromagnets are used as a magnetic chicane bunch compressor which manipulates the electron beam in symmetric C-shape-like trajectories. The chicane creates a dispersive beam where the path length of electrons with a higher momentum is shorter than these with a lower momentum. Consequently, the electron bunch is shorten in the longitudinal axis and led to increase the peak current. The C-chicane requires the electron bunch with the lower energy at the head and the higher energy at the tail of the bunch. To study on the bunch compression in the chicane, we start from the linear optic calculation. The 1st order momentum compaction (R_{56}) which determines the change of the bunch length due to the bunch compressor is defined by $R_{56}=dS/d\delta$, where S is the path length inside the chicane, δ is the relative energy spread. For the symmetric C-chicane, the R_{56}, which is always negative and depends on geometry of the chicane, can be calculated [13] by

$$R_{56} \approx -2\alpha^2 (L_D + 2/3\, L_M), \tag{1}$$

where α is the nominal deflection angle, L_D is the drift length between the 1st and the 2nd bending magnet and L_M is the physical length of the bending magnet. To obtain the maximum compression at the exit of the chicane, the R_{56} of the chicane should match with the energy chirp (h) by

$$R_{56} = -1/h. \tag{2}$$

For the actual chicane design, we decide to the physical length of the magnets to be 65 mm, the distance between magnets of 125 mm to realize the maximum deflection angle to be 35 degree. The energy slits will be installed between the 2nd and the 3rd magnet. The schematic of the magnetic chicane bunch compressor is shown in Fig. 4. From the above equations and the energy chirp from Fig. 3, the calculated deflection angle α for the maximum compression of the chicane are calculated and shown in Fig. 5.

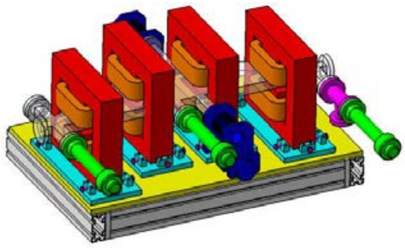

Fig. 4. Schematic of the magnetic chicane

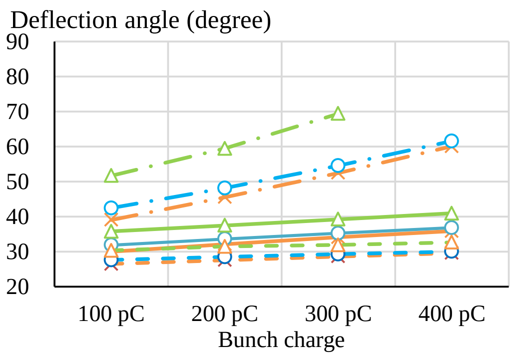

Fig. 5. Deflection angle of the chicane for the maximum compression condition. (The description of the lines and the markers is same as Fig. 2)

From the Fig. 5, the deflection angle of the chicane for the maximum compression is smaller at the higher accelerating voltage and at the lower injection phase. The smaller deflection angle is preferable because the emittance growth due to the 2nd order effect and the focusing in a non-deflecting plane of the chicane are smaller [13]. Therefore, we choose to operate the RF-gun at the accelerating RF-phase of 12 degree with the accelerating voltage as high as possible.

In case of the system operates at a low beam energy, where the space-charge force is dominant, there is a serious non-linear effect during the bunch compression. Therefore, the deflection angles for the maximum compression will be slightly different from the linear calculation in Fig. 5. The beam tracking calculation has been performed by using PARMELA. In this calculation we did not put the energy slit to observe whole beam behavior. A typical longitudinal phase space plot is shown in Fig. 6 in case of accelerating voltage of 80MV/m, laser injection phase of 12 degree and the chicane deflection angle of 27 degree. In this figure, the current profile and the energy distribution are plotted. It is clear that even highest energy among our design system that the longitudinal phase space becomes a spike shape by severe space-charge effect. This spike makes the compressed bunch shape to be complex one. However, we can expect the spike shape part will be removed by proper adjustment of the energy slits. Figure 7 shows the bunch length at the full width at half maximum (FWHM) and the peak current at the undulator entrance for the maximum compression at the accelerating voltage of 60, 70 and 80MV/m and the injection phase of 12 degree without energy slit.

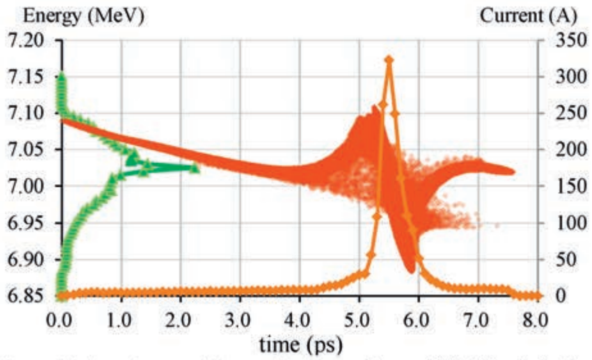

Fig. 6. Energy-time phase space at the undulator entrance at the accelerating voltage of 80MV/m, injection phase of 12 degree and the chicane deflection angle of 27 degree.

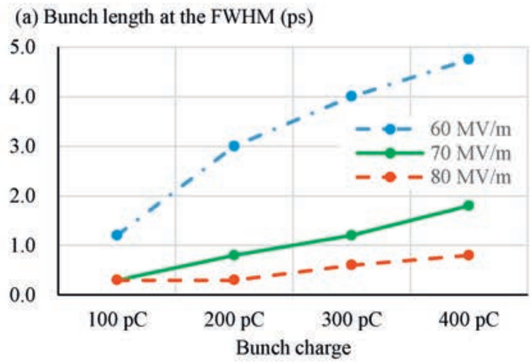

Fig. 7. (a) Bunch length at the FWHM

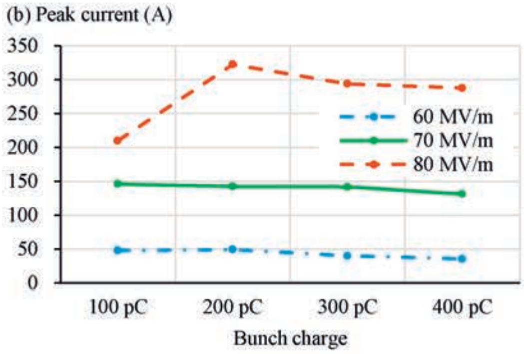

Fig. 7. (Cont.) (b) peak current at the undulator entrance as a function of bunch charge at the accelerating voltage of 60, 70 and 80MV/m and the injection phase of 12 degree.

Note that the deflection angles of the chicane for the accelerating voltage of 60, 70 and 80 MV/m are set to be constant for each bunch charges at 33, 28 and 27 degree, respectively. As the results, the bunch length at the FWHM decreases significantly at the higher accelerating voltage. Then the bunch length of 0.36 ps is obtained at the undulator entrance with the accelerating voltage of 80 MV/m and the bunch charge of 200 pC. The peak current can reach up to 322 A. This result suggests that a higher acceleration voltage and a proper bunch charge would be better to get a higher peak current. However, the acceleration voltage is limited by available RF power and the radiation wavelength. Therefore, there should be upper limitation for the accelerating voltage. In our case, the existing 10 MW RF power should define the maximum acceleration voltage around 70-80 MV/m with our RF-gun. Besides, the higher bunch charge would make the power of THz radiation higher, because the intensity of the CSR radiation is square of the bunch charge. Further study on the optimization of the bunch charge is required to generate an intense THz CSR radiation.

4. Beam Matching for Undulator

The transverse beta function of the electron beam has to be matched with the focusing characteristics of an undulator in order to obtain better spatial radiation performances from the undulator. The triplet quadrupole, which is installed upstream the undulator at the distance of 150 mm, is used for the beam matching. The magnet has the pole face length of 40 mm, an effective length of 55 mm and distance between the pole face of 54 mm. The undulator is a planar Halbach type with a vertical deflection. The undulator has a number of period of 10 and a period length of 70 mm, the measured peak magnetic field of 0.43 Tesla at the undulator gap of 30 mm. We plan to operate the undulator in the ranging from 30 to 50 mm which corresponds to the undulator parameter from 1 to 2.8. In this study, we investigated the beam matching at the highest peak current case as mention in the previous section and at the undulator parameter of 1.3 (the peak magnetic field of 0.2 T). This condition provides the undulator radiation wavelength of 300 μm (1 THz.)

The GPT code was used for the optimization of the triplet quadrupole gradient for the beam matching. The particle distribution at the RF-gun exit obtained from PARMELA was converted and imported to GPT. In this study, we used the RF-gun with the accelerating voltage of 80 MV/m, the bunch charge of 200pC, the laser injection phase at 12 degree and the laser profiles and parameters as mentioned in Table 1 for the beam matching calculation. The electron beam properties at the RF-gun exit are shown in Table 2. The solenoid magnet was not used in this study because the beam has a low bunch charge. The energy slits are adjusted to remove low energy particles which do not contribute to the radiation. For the beam matching by GPT code, the horizontal rms beam size are set to be minimum at the undulator entrance. Meanwhile, the vertical rms beam size are set to be minimum at middle of the undulator. The result of GPT calculation are listed in Table 3. The rms beam size as a function of the distance from the photocathode RF-gun is shown in Fig. 8. As is shown in Fig. 8, we can focus the electron beam in the transverse plane by using a triplet magnets.

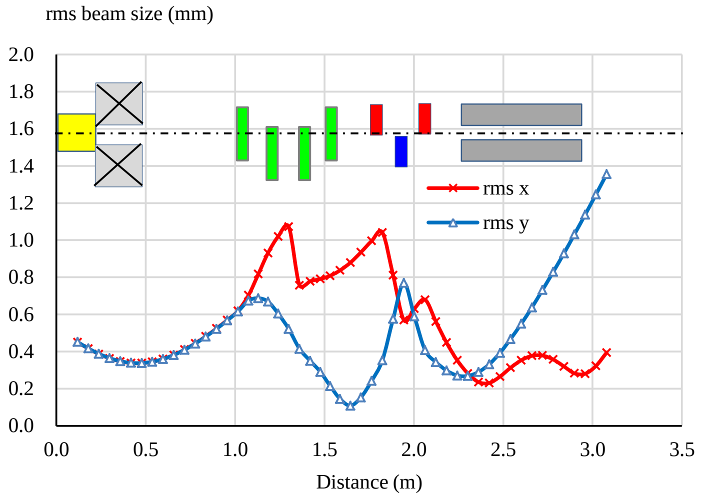

Fig. 8. rms beam size at the accelerating voltage of 80 MV/m and the bunch charge of 200 pC for the undulator parameter of 1.3 (peak magnetic field of 0.2 T)

Table 2. The electron beam properties at the RF-gun exit.

Parameters	Values
Bunch charge (pC)	200
Average energy (MeV)	7.01
rms energy spread (%)	0.71
rms beam size (mm)	$\sigma_x = \sigma_y = 0.45$
normalized rms emittance (mm mrad)	$\varepsilon_{x,\,norm}= 3.49$, $\varepsilon_{y,\,norm}= 3.48$

Table 3. The optimized parameters and the electron beam properties by GPT simulation.

Parameters	Values
Chicane, Triplets	
Chicane peak magnet field (T)	0.153
Energy slits width, offset (mm)	3, 84.4
Triplet quadrupole gradient (T/m)	QF : 2.8, QD : -5.0, QF : 2.7
Electron beam @ Undulator	
Bunch charge (pC)	169.1
Average energy (MeV)	7.03
rms energy spread (%)	0.44
Average rms beam size (mm)	$\sigma_x= 0.31$, $\sigma_y=0.56$
Average normalized rms emittance (mm mrad)	$\varepsilon_{x,\,norm}= 7.24$, $\varepsilon_{y,\,norm}= 18.7$

5. Conclusion

Beam dynamics of the compact seeded THz-FEL system developed in Kyoto University have been investigated by the numerical simulation by using PARMELA and GPT. At the accelerating voltage of 60 MV/m and the injection phase of 12 degree, the average beam energy is low at 5.3 MeV where the space-charge force becomes a serious effect. As a result, the bunch length is quite long and the peak current at the undulator entrance is low at 50 A. Conversely, at the high accelerating voltage of 80 MV/m and the injection phase of 12 degree, the average beam energy is high at 7 MeV. Therefore, for the bunch charge of 200 pC, the bunch length at the undulator entrance is short as 0.36 ps and the peak current at the undulator entrance can reach up over 300 A. Consequently, to generate intense THz radiations, 80 MV/m acceleration voltage is required. The triplet quadrupole can focus the electron beam at the undulator to the average rms beam size in horizontal and vertical of 0.31 and 0.56 mm, respectively. Further numerical study on the bunch charge optimization should be carried out.

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